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TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Chapter 9 of 11

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Chapter 9
HYDROGEN GENERATION FROM STAND-ALONE WIND-POWERED ELECTROLYSIS SYSTEMS

1. PROJECT GOALS

Over recent years, it has been recognized that the combustion of fossil fuels has significantly increased the proportion of carbon dioxide in the atmosphere, with many postulating that this has and will continue to cause changes in global climate. A continuing net global temperature rise and increasing occurrence of extreme climate events are anticipated during the forthcoming century. It is therefore imperative that energy systems based on the utilization of non-fossil sources be developed and exploited as early as possible.

The existence of considerable wind resources in remote places and the high costs of supplying electricity in those places suggest that these might be the first places to benefit from a switch to a hydrogen-based fuel economy. To date, the possibility of using wind power to generate hydrogen has received little attention, despite several major programs investigating the integration of solar photovoltaic power plants with electrolyzers for renewable hydrogen production.

This project was conceived to examine the reasons for this disparity and to explore whether the more irregular power output of a wind turbine (compared to a solar photovoltaic power module) would cause additional problems for a standard water electrolyzer designed for constant power input.

The project sought to determine how best to control a wind turbine to produce a smooth power output, to examine the tolerance of an electrolyzer to fluctuating power inputs, and to design and build a small scale (< 10 kW) stand-alone wind hydrogen production system.

The use of short-term energy storage using batteries or flywheels was also considered, both to provide additional power smoothing and longer term operation of the electrolyzer.

The economics of wind hydrogen systems operating in remote places was assessed.

The major objectives of the project were:

- assessment of hydrogen electrolysis systems undergoing intermittent operation
- comparison of wind turbine operational strategies for dedicated stand-alone hydrogen production
- assessment of overall economics of a wind hydrogen system
- assessment of the suitability of the technology for use in small community power systems

2. GENERAL DESCRIPTION OF PROJECT

A demonstration wind-powered hydrogen production plant has been designed, procured, and constructed, and preliminary tests have been performed. Back-up studies, aimed at determining the tolerance of conventional electrolyzers to input power fluctuations and the potential for smoothing the output from wind power generators, have been carried out in parallel. In all cases, experimental results have been backed up by theoretical analysis and computer simulation, resulting in models of component and system operation at various levels of detail.

The project partners were:

- Energy Research Unit, Rutherford Appleton Laboratory (RAL), United Kingdom
- Casaccia Research Centre, ENEA, Italy
- Institute for Technical Thermodynamics, DLR Stuttgart, Germany
- Department of Engineering (LUED), University of Leicester, United Kingdom

ENEA was responsible for the design, construction, and monitoring of the wind-hydrogen demonstration system at the Casaccia Research Centre; LUED for the development of wind turbine control strategies and for operation of the wind-flywheel storage system at RAL; RAL for dynamic and logistic modeling; and DLR for economic modeling. RAL was also responsible for co-ordinating the work program and providing overall management of the project.

The division of responsibilities between these partners is shown in Figure 9.1.

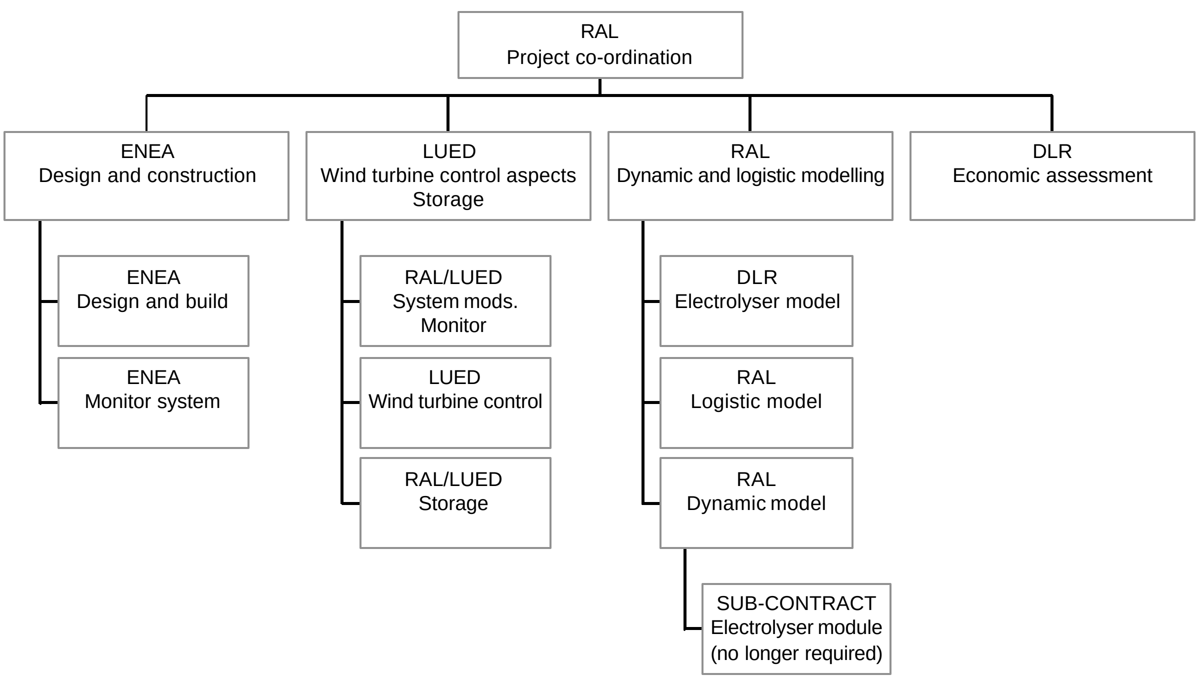

Figure 9.1: Project organization chart

The original project conception was that the demonstration system would be specified and built at ENEA's Casaccia Research Centre in parallel to experiments on the wind turbine control rig at RAL's Wind Test Site. Existing wind turbines on both locations could be utilized. It was planned to develop electrolyzer and systems models in parallel with the experimental program, and to assess the performance with these tools.

The project was funded by the European Commission under the non-nuclear energy (JOULE) program (contract number JOU2-CT93-0413). The project started on 1 April 1994. The original timescale was 2 years, but this proved inadequate for procurement, installation, and testing of the electrolyzer, so a 9-month extension was allowed.

3. DESCRIPTION OF COMPONENTS

3.1 Wind Turbines

Two wind turbines were used during the course of this project. The North Wind L-916, sited on the Wind Test Site at RAL, was modified in various ways to assess the potential for smoothing the power output. The Riva Calzoni M7S, at the ENEA Casaccia Research Centre, was used as the basis for the prototype wind-hydrogen system. Both turbines are very small compared to standard commercial wind turbines, but this was necessary in order to keep the overall project costs within reasonable bounds and it was considered that representative results could be obtained at this scale.

The North Wind L-916 was manufactured by Northern Power Systems of Vermont, USA, and installed at RAL's Wind Test Site in the mid-1980s. It is a down-wind, free yaw design with a two-bladed, teetered rotor of 9 m diameter and a rated power of 14 kW at 11.5 m/s. The turbine is of unusual design and incorporates a number of features not normally found in standard machines designed for grid connected operation:

- power regulation is achieved by a full-span passive pitch mechanism
- the turbine rotor is directly coupled (i.e. there is no gearbox) to the 48-pole synchronous generator with wound field poles.

This turbine was originally designed for fixed speed operation but has been adapted to also run at variable speed for the current project. In fixed speed operation, the generator power is determined entirely by the torque produced by the turbine rotor. Any fluctuation in aerodynamic power, resulting from wind turbulence at the rotor, is directly transmitted to the grid without much attenuation. Correct and rapid control of the turbine rotor torque is therefore important to avoid large fluctuations in the output power. If pitch control is used for this purpose, fast changes in pitch angle are required. With full-span passive pitch and fixed rotational speed, this is difficult to achieve due to the inertia of the blades and the limited pitching effort since no additional contribution from centrifugal forces is available.

In the case of a variable speed wind turbine with a power-electronic converter, the generator torque can be controlled independently from the turbine rotor torque. A change in wind speed results in a mismatch between the instantaneous aerodynamic power and the extracted power and hence in an acceleration or deceleration of the turbine and generator. On reaching rated power, the converter output is kept constant and any surplus in aerodynamic power is used to accelerate the rotor. Due to the position of the center of gravity of the blades and the presence of flyweights at the pitch axes of the rotor, the speed increase leads to higher centrifugal forces. This results in an increase in pitch angle until a new equilibrium position is found, where the aerodynamic power matches the generator power at rated output. For variable speed operation on 50 Hz grid, the variable frequency AC output of the synchronous generator must first be converted into DC power and then inverted into AC power at the grid frequency. This was accomplished by a combination of a simple diode rectifier with a line commutated inverter (LCI).

Thus, variable speed wind turbines can easily be controlled to produce a much smoother power output than the more common constant speed machines.

The wind-hydrogen demonstration system was designed around the existing 5.2 kW Riva Calzoni M7S wind turbine and 330 Ah (nominal) battery energy storage system at the ENEA Casaccia Research Centre near Rome. This turbine, shown in Picture 9.1, drives its synchronous generator at variable speed. The resulting variable frequency AC power output is rectified and supplies a DC bus that feeds the electrolyzer and the battery storage.

Picture 9.1: The Riva Calzoni M7S wind turbine

The wind regime on this site is not particularly favorable (annual mean wind speed of 2.7 m/s), which led to a specification of power rating for the electrolyzer lower than would be optimal for a more windy site. Modeling results carried out by project members suggested that cost and operational benefits could be realized by down-rating the electrolyzer with respect to the wind turbine. For such a stand-alone application, the economic optimum depends on the wind regime of the site, the rating of additional energy storage components, and the utilization potential for excess electricity. For the Casaccia site, a preliminary estimate of the most suitable electrolyzer rating was carried out using the E-WISDA logistic simulation program, developed by ENEA in a previous JOULE project. These studies resulted in the conclusion that a 1 kW_e electrolyzer would be suitable for this application.

3.2 Electrolyzer

The main criteria driving the electrolyzer specification were:

- simple, fully automatic operation
- simple installation (in terms of auxiliary equipment)
- favorable behavior in intermittent operation
- access to main operating parameters for experimental purposes
- limited cost (due to budget limitations)

Electrolyzers at this rating did not prove to be readily available. A tender exercise was carried out between four manufacturers: The Electrolyzer Ltd. (Canada), Ammonia Casale SA (Switzerland), von Hoerner System GmbH (Germany), and Idroenergy (Italy).

The main features of the electrolyzer specification were:

- nominal power of 1-2 kW
- manufacturer to state whether pressurized or atmospheric pressure operation
- nominal voltage preferably in the range 30 - 110 V_{DC}
- able to withstand intermittent operation
- safely withstand operation at very low current values
- a control system able to perform automatic operation for start-up, operation, stand-by, and shutdown
- guarantee on safety aspects and fulfillment of standard regulations; inclusion of internal safety procedures, which shall be activated, if necessary, by the control equipment without any external intervention
- inclusion in the delivery of a water treatment section, in order to permit operation of the plant from a main water supply
- protection devices including, at least:
  - maximum current
  - maximum voltage
  - minimum current (if applicable)
  - minimum voltage (if applicable)
  - maximum pressure
  - maximum temperature
  - minimum temperature (if applicable)
  - maximum concentration of oxygen in hydrogen
  - low inert gas pressure (if applicable)
  - explosion meter inside the cabinet
  - water conductivity
- ambient temperature in the range -10°C to + 40°C
- provision of basic sensors and transducers

The tender from von Hoerner System GmbH was selected since it was the only one reasonably close to the project budget. The system had the following main features:

- 2.25 kW nominal power

- 50 V nominal voltage
- pressurized operation (20 bar)
- fully automatic operation (with the exception of an electric current limitation of less than 20 amps during start-up, to be implemented separately)
- no need for system inertization and cell polarization after shutdown
- ability to hold the internal pressure for some days (or weeks) in “stand-by” condition, and immediate re-start of the process whenever the current was supplied again

The measurement of hydrogen flow rate was derived from pressure and temperature measurements performed on a 50 liter/20 bar bottle positioned at the hydrogen gas outlet.

The electrolyzer is shown in Picture 9.2. It was designed to operate in three possible “normal” states: start-up, normal operation, and shut-down.

Picture 9.2: The 2.25 kW electrolyzer

Start-up: The start-up phase corresponds to starting the process with an initial pressure less than the nominal (20 bar). During start-up, the device operates at variable current, with the following limitation: I<20 A unless the internal pressure is >3 bar. At higher pressures, low current levels are not recommended, in order to reach the nominal pressure as soon as possible. During start-up, no gas is sent to the storage bottle, while some gas is vented to the atmosphere in order to maintain its quality within safety limits.

Normal operation: When the nominal pressure is reached, the device begins to supply hydrogen to the storage bottle. The current can be varied in a range from (nominally) zero to maximum current (47 A). However, current values lower than 20 A are not recommended in order to maintain a good gas quality.

Stand-by: The stand-by phase corresponds to operation with zero input current. In such conditions, the device does not produce any gas flow to the bottle but should be able to hold the internal pressure (for some days or weeks, as claimed by the manufacturer, von Hoerner System (vHS) GmbH), while waiting for restoration of the current supply (i.e., as soon as wind or solar power is available).

3.3 Other components

The step down DC-DC converter was selected after a detailed market evaluation. It comprises three 800 W units (each a standard industrial production isolated converter manufactured by Power Control Systems) working in parallel that can supply a voltage linearly variable from 7 to 50 V, controlled by a 0-10 V_{DC} signal.

The battery storage unit comprises 54 series-connected lead-acid cells with a nominal voltage of 2 V each and a nominal capacity of 330 Ah, for a total nominal capacity of 35.6 kWh. The full extent of this large capacity is probably not completely available, due to battery aging (the batteries were installed in 1988). No measurements have been made in order to determine the currently available capacity but it is anticipated that this should still be in the range of some tens of kWh.

The project site is shown in Picture 9.3.

Picture 9.3: Project Site at ENEA Casaccia

4. INTEGRATION OF COMPONENTS

4.1 Matching of components

The main criteria in designing the plant were:

- to exploit as much as possible existing equipment, comprising the 5.2 kW wind turbine, battery storage rated at 330 Ah - 110 V_{DC}, and two dump loads
- to permit the investigation of different control strategies for wind-hydrogen generation

Two options were examined for the electrolyzer supply from the wind turbine generator (WTG):

- introduction of a voltage transformer at the WTG output, with direct connection of the electrolyzer and of a section of the battery pack to the common 50 V bus
- connection of the electrolyzer through a DC-DC controllable converter

The second option was selected since the first would have had frequency limitations and would have imposed the need to heavily modify the existing electric board, controllers, and 110 V lines. In addition, such a converter permits a degree of freedom in the electrolyzer current.

4.2 Basic scheme of plant

The basic scheme for the complete plant is shown in Figure 9.2.

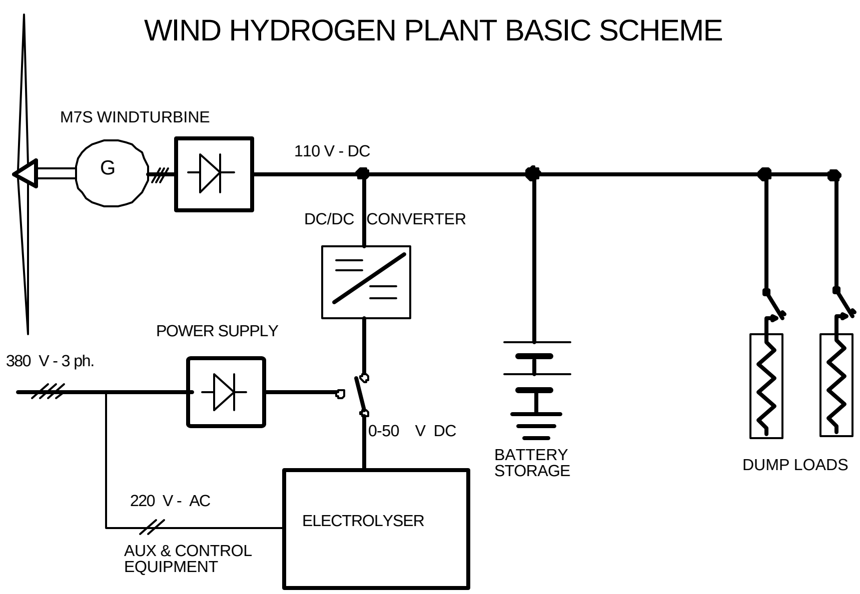

Figure 9.2: Basic scheme for demonstration wind-powered hydrogen generation plant, ENEA Casaccia Research Centre

The plant comprises the wind turbine, the electrolyzer unit complete with its built-in controllable power supply, battery storage, a DC-DC controllable converter, and two dump loads (0.5 and 2 kW) controlled by two voltage actuated relays. The auxiliary equipment (electrolyzer pumps, valves, control equipment, and water demineralization unit) for the demonstration plant are supplied by the grid for convenience. Clearly, for a truly autonomous system these would need to be supplied from the wind turbine and battery.

The M7S wind turbine drives its synchronous generator (G in Figure 9.2) at variable speed. The maximum voltage is limited by a field regulator, acting on the field current. The resulting variable frequency AC power output is rectified and supplies a DC bus that feeds the electrolyzer and the battery storage.

The electrolyzer plant can be operated in two modes:

- **wind-powered**: The electrolyzer current is controlled by the DC-DC step down converter, while the current to the battery storage will not be controlled. The battery will act as an energy buffer, and the dump loads are controlled in order to limit the maximum voltage to the battery to prevent overcharging (and to limit the generator voltage in case of a controller fault, which could damage the turbine)
- **from the controlled power supply:** The electrolyzer is supplied by the controllable power supply, either manually or PC-controlled to emulate the operation from a different type of plant (e.g. using measured RAL time series power data from the North Wind L-916 wind turbine, or other synthesized time series of electrolyzer current). The manual operation of the power supply being useful to execute tests or carry out a functional check of the electrolyzer behavior

Since the project is concerned only with the production of hydrogen, not its large scale storage or utilization, the product gases are released to the atmosphere. The hydrogen, stored initially in the 50 liter bottle, is released by a maximum pressure valve set at 20 bar, while the oxygen is released directly to the atmosphere. Three oxygen pipes and four hydrogen pipes have been installed (comprising gas release coming from normal gas production, safety valves, and supplies to gas quality measurement equipment).

4.3 Plant control

The main components of the control scheme are shown in Figure 9.3:

- WTG centrifugal speed controller, that acts on the blade pitch angle in order to limit the wind turbine speed to less than 300 r/min (on low speed shaft)
- WTG voltage controller, an electronic device chopping the field current in order to limit the maximum generator voltage
- dump load controllers, the connection state of the two resistor dump loads (0.5 and 2.0 kW) controlled by two voltage actuated relays that limit the maximum voltage in case of a fault in the generator voltage controller
- electrolyzer controller, a Klockner Moeller PLC (programmable logic controller) of the SUCOS PS3 series, that can autonomously manage all operating and fault conditions of the electrolyzer
- plant controller, that controls the connection state of the electrolyzer to the DC bus and the amplitude of current supplied to the electrolyzer (when connected). A PC-based solution has

been selected for its flexibility and ability to be used also for the experimental data acquisition and processing.

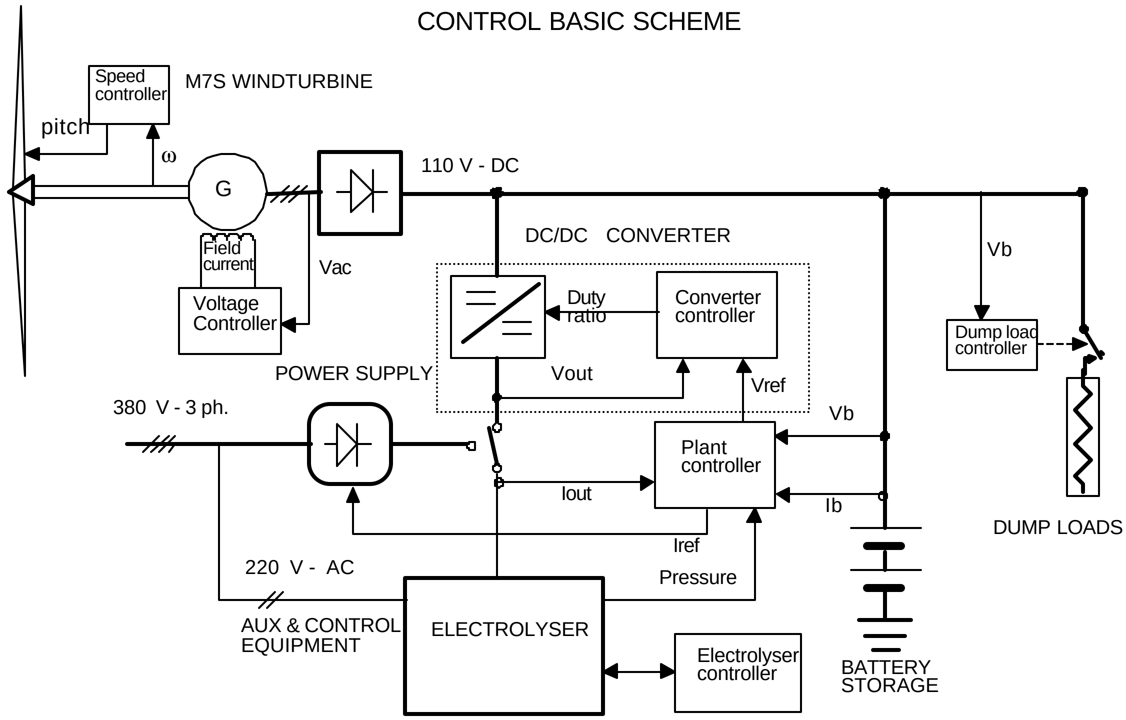

Figure 9.3: Scheme of control system for demonstration wind-powered hydrogen generation plant, ENEA Casaccia Research Centre

The basic control strategy is quite simple. The electrolyzer is:

- **"connected"** if the state of charge (SOC) of the battery is sufficient and the generated power > 0 for a significant time, or
- **"disconnected"** if the SOC of the battery is insufficient for a significant time.

The simplest way to control the electrolyzer current is to "simulate" the direct connection of the electrolyzer to the DC bus. In fact, neglecting its power losses, the DC-DC converter can be controlled in such a way as to be ideally "transparent.

A further objective of the project was to permit the investigation of the electrolyzer behavior in connection with different plant configurations, namely with direct connection of the electrolyzer to the Riva Calzoni wind turbine and its associated battery storage bank, or with the North Wind wind turbine at RAL and a more limited amount of flywheel energy storage capacity, or with some other simulated configuration. The computer is able to control the DT-2801 output board in such a way as to control the current delivered by the built-in power supply, according to the time series of current/power.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 Electrolyzer

The electrolyzer was commissioned by vHS by the end of September 1996. During the first test campaign, a number of faults and malfunctions developed in the electrolyzer operation. Much of the experimental effort in the first year of testing was therefore devoted to understanding the causes and implementing and testing modifications to the electrolyzer assembly.

Most of the problems were due to high impurity levels of hydrogen in oxygen during operation at low current levels and apparently high impurity levels of oxygen in hydrogen after some hours of stand-by operation, both conditions leading to alarms and automatic plant shutdown. In addition, the rate of pressure loss during stand-by was very high.

The detected causes of these malfunctions were:

- small gas leakage from flanges and pipe connections
- pollution of sensed gas due to diffusion of external air inside the sensor lines during stand-by (specifically this was the cause of the apparently poor hydrogen quality)
- excessive pressure drop mainly due to gas flow to analyzers
- insufficient internal insulation of the anode

After thorough investigation, a number of remedies were introduced:

- checks and tightening of all flanges and pipe connections
- installation of voltage-controlled valves in the gas quality sensor lines in order to prevent pressure drop during stand-by and to prevent pollution of sensor atmosphere (since original plastic non-return valves were found to have been inadequate)
- substitution of Teflon pipes with PVC pipes in gas quality measurement lines

These actions solved most of the problems, with the exception of the bad oxygen quality at low currents. At this stage, the cell stack was returned to the manufacturer who introduced improved anode insulation and complete insulation of the end flange with a special coating. Following these modifications, further tests showed that:

- behavior in intermittent operation is satisfactory, although during stand-by,the pressure drop is still not negligible (approximately 15 bar in 60 hours) - this is probably due, at least in part, to the disconnection of pipework to allow the cell stack modifications and may be solved by further tightening and substitution of seals
- the measured minimum continuous current level for acceptable oxygen quality (defined as 3 % hydrogen in oxygen) is around 25 A (this is of little or no concern if the oxygen is a waste product to be vented to atmosphere)
- hydrogen quality is good, with impurity levels typically of the order of 0.15-0.35% oxygen in hydrogen, for current levels as low as 15 A or less, thereby permitting operation at very low capacity factors

The measured V-I characteristic, shown in Figure 9.4, referred to two typical electrolyte temperatures (measured at the electrolyte outlet, not directly in the stack, which could be 15^{o}C higher) representative of “cold” and “warm” conditions. The data are extrapolated from a number of measurements at different temperatures, since control of temperature for experimental purposes cannot be easily implemented.

The overall cell stack efficiency (relative to the lower heating value for hydrogen) has been found to be typically around 40%, with a maximum of 45% around nominal current. These values are very low compared to the values in excess of 60% found for the HYSOLAR Electrolyzer 2 at DLR.

Most recently, a fault in a non-return valve has allowed KOH solution to enter and damage the demineralization unit pump, causing a cessation of activity on the plant.

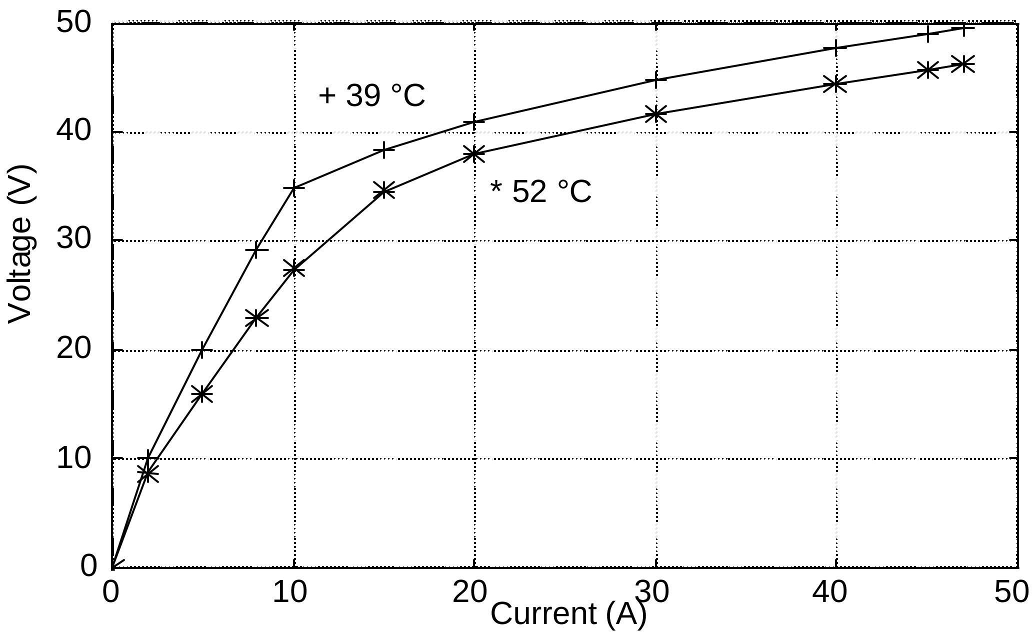

Figure 9.4: Electrolyzer vHS voltage-current characteristics (data extrapolated to 39°C and 52°C)

5.2 Wind Turbine

On the wind turbine side, comparing gain functions between wind speed and electrical output power, it has been demonstrated that variable speed operation can achieve considerable power smoothing benefits:

- below rated wind speed the inertia of the wind turbine acts as a low-pass filter with a time constant approximately equal to the inertia time constant of the wind turbine
- above rated wind speed the output power can be kept virtually constant if the wind turbine is allowed to exceed the rated speed of the equivalent fixed speed machine

In the case of a variable speed wind turbine, equipped with a synchronous generator, the decoupling provided by the AC-DC(/AC) interface removes the resonant mode of direct grid coupling as well as the power fluctuations due to tower shadow and rotational sampling of wind shear over the turbine rotor. The power smoothing is typically effective on time scales of up to 20 seconds.

The power smoothing potential of the variable speed wind turbine can be further enhanced by means of a synchronously linked flywheel energy store, as demonstrated in the system at RAL, or by a battery bank, as used at ENEA. Drawbacks are the increased complexity of system layout with its associated costs, standing losses (which may be proportionately quite large in the flywheel system), and energy transfer losses.

5.3 Further comments relating to intermittent electrolyzer operation

Electrolyzer technology for constant power applications is well established, but the implications of operation with intermittent power sources are little researched. Due to the problems experienced in procuring and commissioning the vHS electrolyzer, additional laboratory tests were carried out by DLR in Stuttgart on the HYSOLAR Electrolyzer 2 to explore the implications of operation with intermittent power sources. These tests indicate that:

- with regard to short term operation, power fluctuations have no significant effect on the overall electrical stability of the electrolyzer
- the magnitude of pressure fluctuations increases and the product gas purity declines, compared to operation at the equivalent constant mean power input
- the decline in product gas purity appears to be affected by power variations on the scale of a few minutes rather than a few seconds

Such medium term and long term power fluctuations need to be taken into account in the design of the electrolyzer (in particular, whether pressurized, or not, and whether potential stabilization is required for the electrodes) and the overall system (e.g. size of battery/flywheel energy storage, control strategy).

The electrochemical effects of operation for long periods (i.e. year after year) with an intermittent power source remain uncertain and lie beyond the scope of the current project. The selection of the most suitable type of electrode, in particular whether to use rare materials and technically advanced but expensive production processes, must lie in the resolution of this question.

6. DATA ACQUISITION

Due to the problems with the electrolyzer plant, few experimental results were obtained.

The basic measurements provided were:

- DC voltage and current to the electrolysis section
- power to auxiliaries
- power to heating device
- impurity level of oxygen in hydrogen (with sample gas treatment including cooling, washing and drying)
- levels of hydrogen and oxygen in the gas separators
- electrolyte temperature in the cell block
- hydrogen flow rate (from integral measurement derived from pressure and temperature measurements performed on a 50 liter/20 bar bottle positioned at the hydrogen gas outlet)

Results were obtained for:

- basic commissioning tests
- hydrogen production tests (volumetric flow rate (Nm^3/h) and efficiency as a function of current and electrolyte temperature)
- impurity levels as a function of current
- dynamic response of the electrolyzer to voltage steps
- variable current tests simulating output from the RAL North Wind turbine
- operation with supply from Riva Calzoni M7S wind turbine

7. SIMULATION

The various systems and their components have been analyzed using a range of different computer models:

- the electrolyzer model SIMELINT has been used to simulate electrolyzer behavior (including overall production volume and gas impurity levels) when connected to either constant or intermittent power sources, and thereby to examine promising control strategies
- a logistic system model, developed in SIMULINK, has been used to examine the effect of component sizing and the hydrogen production potential of sites with different annual mean wind speeds
- an economic model has been used to analyze the overall cost of hydrogen from differently sized systems and to provide a breakdown of how the different components contribute to that cost

Unfortunately the electrolyzer for the demonstration system was supplied too late to be included in the validation of the electrolyzer and system models. The electrolyzer model was validated by the DLR project partners using their Metkon electrolyzer (nominal power 10 kW, constructed within the HYSOLAR demonstration program). The characteristics for the same electrolyzer were used within the system model.

The optimal sizing of the electrolyzer relative to the wind turbine is a complicated function of the site meteorology, including annual mean wind speed (i.e. annual energy production), capital costs of components, gas quality, and the specific application, including availability (or otherwise) of alternative markets for some or all of the wind-generated electricity. For a given application and site, the adoption of a suitable control strategy can significantly increase the annual yield of hydrogen. Example cases studied include:

- an electrolyzer rated at 80% of the power rating of the accompanying wind turbine, where the slight decrease in volume of production and higher auxiliary energy costs (cooling energy) must be offset against the reduced capital cost of the electrolyzer
- an electrolyzer with the same power rating as the accompanying wind turbine, where additional energy storage is available (e.g. batteries) and the electrolyzer is operated continually at part load, resulting in higher overall efficiency and hence an increase in the volume of hydrogen produced

Sizing studies within the project demonstrated that small scale installations, such as the prototype wind-hydrogen plant discussed herein, are not economic, due to the high capital cost of all the ancillary equipment. For this reason wind-hydrogen generation systems are only likely to be viable at large scale (> 1 MW).

8. PUBLIC ACCEPTANCE AND SAFETY ISSUES

Public acceptance was not an issue for the current project.

The design and specification phase of the project took much longer than expected, in part due to the complexity of technical details and the safety regulations concerned with hydrogen devices. This latter point can prove time-consuming for non-specialists in hydrogen technology (which will usually be the case for such an immature technology) and should be considered by anyone planning future projects.

The main aim in defining the plant arrangement was to assure a high safety level in a simple way. To this purpose, the components are located in two different barracks:

- **main barrack**: switchgear cabinet containing all the equipment pertaining to the wind turbine, battery, and dump load control; switchgear cabinet containing the equipment for electrolyzer supply and control (PLC controller); the DC-DC converter unit; data acquisition and plant control equipment
- **secondary barrack**: electrolyzer; water supply/demineralization unit; storage bottle

In order to fulfill safety standards, the electrolyzer barrack includes only a very limited electric plant with IP55 protection. The electrolyzer cabinet is completely gas-proof, and the internal electrical components are explosion proof; inside the cabinet an explosion meter is provided that sends a signal to the electrolyzer PLC in case an explosive environment develops inside the cabinet.

As a further provision, two vents for the internal air have been installed in the barrack roof; one of these vents air from the barrack, the second vents the cabinet internal atmosphere by means of a connection pipe to the cabinet roof.

To fulfill safety standards, the hydrogen pipes release the gas at a height of 5 m from the ground (the standard prescribes a minimum distance of 7.5 m from the electric plants of the main barrack, because they are not explosion proof nor IP55 qualified). To this purpose, the pipes are inserted inside a lattice pole, normally used for holding anemometer sensors. The lattice support structure protects the pipes from possible physical strikes and carries lightning protection.

All the exhausts are made with a gooseneck end in order to avoid water intrusion and a special non-return, flame-arrester valve has been installed in the main pipe end (exhaust from the 50 liter bottle).

9. OTHER EXPERIENCES

The project was carried out against a background of declining government support for hydrogen research in both Italy and Germany, where ENEA and DLR are based. Government support in the UK, where RAL and University of Leicester reside, started out and remains virtually nil.

10. FUTURE POTENTIAL - FUTURE PLANS

The prototype wind-hydrogen plant has had many problems, almost entirely related to the electrolyzer. This indicates an immature and unreliable technology. Further funding to operate the plant has not been forthcoming, but future work must begin by fixing the “conventional” problems relating to gas leaks and pressure drops during stand-by operation, and then investigate the causes of the low efficiency obtained. A long term program is then required to:

- characterize efficiency and gas quality with variable current operation over long periods of time
- run long term tests for estimation of cell life in this application
- optimize control strategy
- estimate optimum size for back-up battery store

On a wider front, the effects of medium term and long term power fluctuations need to be taken into account at the design stage of the electrolyzer (in particular, whether pressurized, or not, and whether potential stabilization is required for the electrodes) and the overall system, including provision for energy storage (e.g. size of battery/flywheel energy storage, control strategy). There remains much work to be done towards defining the optimum control strategy for the system and hence the optimum relative sizing of the electrolyzer. In particular, the trade-off between the higher efficiency and overall yield during part-load operation of an equally sized (to the wind turbine) electrolyzer and the higher capital equipment cost (relative to a smaller electrolyzer) need to be examined on a case by case basis. Some further product development is required to make a truly autonomous system.

The electrochemical effects of operation for long periods (i.e. year after year) with an intermittent power source remain uncertain and lie beyond the scope of this project. The selection of the most suitable type of electrode, in particular, regarding the use of rare materials and technically advanced but expensive production processes, remains an open question that can only be resolved by long-term back-to-back testing of electrolyzers with intermittent and constant power supplies. The experiments should examine whether there is any deterioration of yield with time and whether there is any physical deterioration of the electrodes.

In the longer term, it is required to identify niche markets where such a system can be applied. This is likely to be in a remote site or somewhere where high quality hydrogen and oxygen are required as raw materials for some industrial process. In this latter application, the renewable hydrogen and oxygen must compete with more costly technical gases, exploiting the high purity of the gases produced by electrolysis. A plant in such a situation would provide improved security of supply, particularly if the site has a good wind resource.

The capital cost of a wind turbine and the unit cost of wind-powered electricity have decreased markedly over recent years. The specific capital cost (DM/kW$_e$) of the electrolyzer would be at least 2.5 times that of the wind turbine for a 1 MW size plant. Clearly, if wind-hydrogen systems are ever to become good economic propositions, the capital cost of the electrolyzer must be decreased considerably. This will only be achieved through a concentrated program of research and development to drive down costs. Without such a program, the environmental benefits of renewable hydrogen are unlikely to be realized anywhere other than in isolated communities and niche markets.

11. CONCLUSIONS

A demonstration wind-powered hydrogen production plant has been designed, procured, and constructed, and preliminary tests have been performed. Back-up studies, aimed at determining the tolerance of conventional electrolyzers to input power fluctuations and the potential for smoothing the output from wind power generators, have been carried out in parallel. In all cases, experimental results have been backed up by theoretical analysis and computer simulation, resulting in models of component and system operation at various levels of detail.

Hydrogen produced from wind power represents a clean and versatile fuel, which can be handled similarly to natural gas. It is a storable, versatile energy carrier which has negligible environmental effects compared with the combustion of fossil fuels.

It has been demonstrated that there are no insurmountable technical problems associated with hydrogen production by wind-powered electrolysis. However, intermittent electrolysis technology is at a comparatively early stage of development, resulting in a scarcity of technical data and operational experience. The following general observations can be made concerning the implementation of the demonstration system at the ENEA Casaccia Research Centre:

- the complexity of technical details and the safety regulations concerned with hydrogen devices can make system design and specification time-consuming for non-hydrogen specialists
- from the limited number of tests carried out to date, it is not apparent that operation with variable current or intermittent supply presents any major stability or general operational problems for the electrolyzer; on the other hand, the production and gas quality data show that this particular electrolyzer suffers reduced performance when operated at low capacity factors, and auxiliary storage equipment seems necessary to permit successful operation during periods of moderate wind speed
- the frequency and variety of alarm occurrences is unacceptable and demonstrates the relative immaturity of electrolyzer technology
- the longer term effects of intermittent operation are beyond the scope of the current project and should be addressed by a future project

Further development is required to implement a truly autonomous system. This should cover both control strategy issues and product development to supply power to the auxiliary equipment (electrolyzer pumps, valves, control equipment, water demineralization unit) from the wind turbine/battery system.

Costs of hydrogen from renewable energy sources are currently uncompetitive with fossil fuel derived hydrogen, or, indeed, with grid-connected electrolyzers operated at constant current. It is therefore likely that hydrogen derived from renewable sources will first be used in niche markets where conventional fossil fuels are expensive (e.g. remote areas, islands, and decentralized electricity supply systems) or where high purity gases are required on site. In the latter case, purity levels will, in general, be higher than for fossil fuel derived hydrogen (at least, before expensive purification) and the purity may be further controlled by selecting a suitable operating strategy for the plant.

At current energy prices, hydrogen is only likely to be produced from wind power if excess electricity is available. Such a situation might occur in weak grids that have a limit on the penetration of wind energy.